



# Design of a Glenn Research Center Solar Field Grid-Tied Photovoltaic Power System

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# **Design of a Glenn Research Center Solar Field Grid-Tied Photovoltaic Power System**

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## **Summary**

The NASA Glenn Research Center (GRC) designed, developed, and installed, a 37.5 kW DC photovoltaic (PV) Solar Field in the GRC West Area in the 1970s for the purpose of testing PV panels for various space and terrestrial applications. The PV panels are arranged to provide a nominal 120 VDC. The GRC Solar Field has been extremely successful in meeting its mission. The PV panels and the supporting electrical systems are all near their end of life. GRC has designed a 72 kW DC grid-tied PV power system to replace the existing GRC West Area Solar Field.

The 72 kW DC grid-tied PV power system will provide DC solar power for GRC PV testing applications, and provide AC facility power for all times that research power is not required. A grid-tied system is connected directly to the utility distribution grid. Facility power can be obtained from the utility system as normal. The PV system is synchronized with the utility system to provide power for the facility, and excess power is provided to the utility for use by all.

The project transfers space technology to terrestrial use via nontraditional partners. GRC personnel glean valuable experience with PV power systems that are directly applicable to various space power systems, and provide valuable space program test data. PV power systems help to reduce harmful emissions and reduce the Nation's dependence on fossil fuels. Power generated by the PV system reduces the GRC utility demand, and the surplus power aids the community.

Present global energy concerns reinforce the need for the development of alternative energy systems. Modern PV panels are readily available, reliable, efficient, and economical with a life expectancy of at least 25 years. Modern electronics has been the enabling technology behind grid-tied power systems, making them safe, reliable, efficient, and economical with a life expectancy of at least 25 years.

The report concludes that the GRC West Area grid-tied PV power system design is viable for a reliable, maintenance free, long life power system that is of significant value to NASA and the community.

## **Introduction**

The NASA Glenn Research Center has a wealth of experience in photovoltaic power systems. The work was done under the Hybrid Power Management (HPM) Program. The GRC Electrical and Electromagnetics Branch initiated the HPM Program for the GRC Technology Transfer and Partnership Office. HPM is the innovative integration of diverse, state-of-the-art power devices in an optimal configuration for space and terrestrial applications. The appropriate application and control of the various power devices significantly improves overall system performance and efficiency. Applications include power generation, transportation systems, biotechnology systems, and space power systems.

A PV power system can either be a stand alone, off-grid system, or a grid-tied system. An off-grid PV system provides local power only. A grid-tied PV system is connected directly to the utility distribution grid. Facility power can be obtained from the utility system as normal. The PV system is synchronized with the utility system. The PV system provides power for the facility, and excess power is provided to the utility.

Photovoltaic power systems have tremendous potential. The 89 petawatts of sunlight reaching the Earth's surface is approximately 6,000 times greater than the 15 terawatts of average power consumed by

the human population. PV generation has the highest power density of renewable energies with a global mean of 170 W/m<sup>2</sup> (Ref. 1). PV is entirely pollution free during use. PV system production end wastes and emissions are manageable utilizing existing pollution controls. End-of-use recycling technologies are under development to minimize negative environmental effects. PV systems can operate with minimal operator intervention or maintenance after initial setup.

Grid-tied PV power systems provide many benefits. Operating costs of a PV power system are low compared to conventional power technologies. PV can displace the highest cost electricity during times of peak demand in most climatic regions, and thus reduce grid loading. Net Metering is often used, in which independent power producers, such as PV power systems, are connected to the utility grid via the customers' main service panel and meter. When the PV power system is generating more power than required at that location, the excess power is provided to the utility grid. The customer pays the net of the power purchased when the on-site power demand is greater than the on-site power production and the excess power that is returned to the utility grid.

Grid-tied PV power systems can be used locally thus reducing transmission/distribution losses. Transmission/distribution losses in the U.S. were approximately 7.2 percent in 1995 (Ref. 2), thus providing a potential for significant energy savings.

The GRC West Area 72 kW grid-tied PV power system can be used for photovoltaic power testing, as it has traditionally, and also be used to provide grid-tied utility power when photovoltaic research power is not required. Theoretical power generation has been determined for the GRC West Area 72 kW grid-tied PV power system.

## **Analysis**

### **Predicted Power Generation**

The National Renewable Energy Laboratory has developed a calculator to determine the energy production of grid-tied PV power systems throughout the world. The calculator is based upon the work of David F. Mennicucci (Ref. 3).

The calculator creates hour-by-hour performance simulations that provide power estimated monthly and annual energy production in kilowatts and energy value. Users can select a location and choose to use default values or their own system parameters, for size, electricity cost, array type, tilt angle, and azimuth angle. The calculator can provide hourly performance data for the selected location.

The calculator uses typical meteorological year weather for the selected location, and determines the incident PV array solar radiation and the PV cell temperature for each hour of the year. The DC energy for each hour is calculated from the PV system DC rating and the incident solar radiation, and then corrected for the PV cell temperature. The AC energy for each hour is calculated by multiplying the DC energy by the overall DC-to-AC derating factor and adjusting for the inverter efficiency as a function of the load. Hourly values of AC energy are summed to determine monthly and annual AC energy production.

A PV system is rated upon its nameplate DC power rating. This is determined by adding the PV panel power listed on the nameplates of the PV panels in watts (W), and dividing the sum by 1,000 to convert the rating to kilowatts (kW). PV panels are rated for standard test conditions of 1,000 W/m solar irradiance, and 25 °C PV panel temperature.

The PV system AC rating is determined by multiplying the nameplate DC power rating by an overall DC-to-AC derating factor. The DC-to-AC derating factor account for losses from the DC nameplate power rating, and is the mathematical product of the derating factors for the components of the PV system. The derating factor components includes PV array nameplate DC rating accuracy, inverter and transformer losses, mismatch, diode and connection losses, DC wiring losses, AC wiring losses, PV array contamination, system availability, and shading.

The derating factor for PV array contamination accounts for snow and other foreign matter on the surface of the PV array that prevents solar radiation from reaching the solar cells. PV array contamination

is location and weather dependent. There are greater contamination losses in high-traffic, high pollution areas with infrequent rain. Snow reduces energy produced, and the severity is a function of the amount of snow and the duration that it remains on the PV array. Snow remains the longest when sub-freezing temperatures prevail, small PV array tilt angles prevent snow from sliding off, the PV array is closely integrated onto the roof, and the roof, or another structure in the vicinity, facilitates snow drift onto the array.

The tilt angle for a fixed array is the angle from horizontal of the inclination of the PV array. Thus a tilt of 0° is a horizontal array, and a tilt of 90° is a vertical array. An array is normally tilted at the location's latitude. This normally maximizes annual energy production. Increasing the tilt angle favors energy production in the winter, and decreasing the tilt angle favors energy production in the summer.

The azimuth angle for a fixed array is the angle clockwise from true north that the PV array faces. An azimuth angle of 180° (south-facing) is normally used for locations in the northern hemisphere, and 0° (north-facing) for locations in the southern hemisphere. This normally maximizes energy production. For the northern hemisphere, increasing the azimuth angle favors afternoon energy production, and decreasing the azimuth angle favors morning energy production. For the southern hemisphere, decreasing the azimuth angle favors afternoon energy production, and increasing the azimuth angle favors morning energy production.

The monthly and yearly energy production estimates are modeled using the selected PV system parameters and weather data that are typical or representative of long-term averages. Weather patterns vary from year to year, so the model is a better indicator of long-term performance than of performance for a particular month or year. PV performance is largely proportional to the solar radiation received, which may vary from the long-term average by 30 percent monthly and 10 percent yearly. For these variations, and the uncertainties associated with the weather data and model, future months and years may have actual PV performance that differs from the model. The variations may be as much as 40 percent for individual months, and up to 20 percent for individual years. Long-term performance over many years is expected to be accurate within 10 percent.

There are other factors that affect model accuracy. Nearby buildings, objects, or other PV arrays and array structures that shade the PV array will cause a reduction in actual energy production from the model. Snow or other contamination of the PV array will cause an inconsistency with the model. There is a reduction in power generation over time that is not factored into the model. Aging is due to weathering of the PV array, and is typically 1 percent per year.

The predicted AC energy for a grid-tied 72 kW DC PV power system located in Cleveland, Ohio is shown in Table 1. The assumptions made for this prediction is that the PV array is crystalline silicon, the PV array is fixed at a tilt of 41.4°, the PV array azimuth is 180.0°, and the DC-to-AC derating factor is 0.770. The predicted AC energy is shown graphically in Figure 1.

TABLE 1.—PREDICTED ENERGY FOR A GRID-TIED  
72 kW DC PHOTOVOLTAIC POWER SYSTEM  
IN CLEVELAND, OHIO

Month	Solar radiation, kWh/m <sup>2</sup> /day	AC energy, kWh
January	2.49	4403
February	3.34	5284
March	4.09	7042
April	4.94	7975
May	5.48	8763
June	5.56	8319
July	5.55	8544
August	5.47	8467
September	4.90	7494
October	3.91	6359
November	2.18	3398
December	1.68	2749
Total annual	4.14	78797

## Predicted AC Energy for a 72 kW DC PV System in Cleveland, Ohio

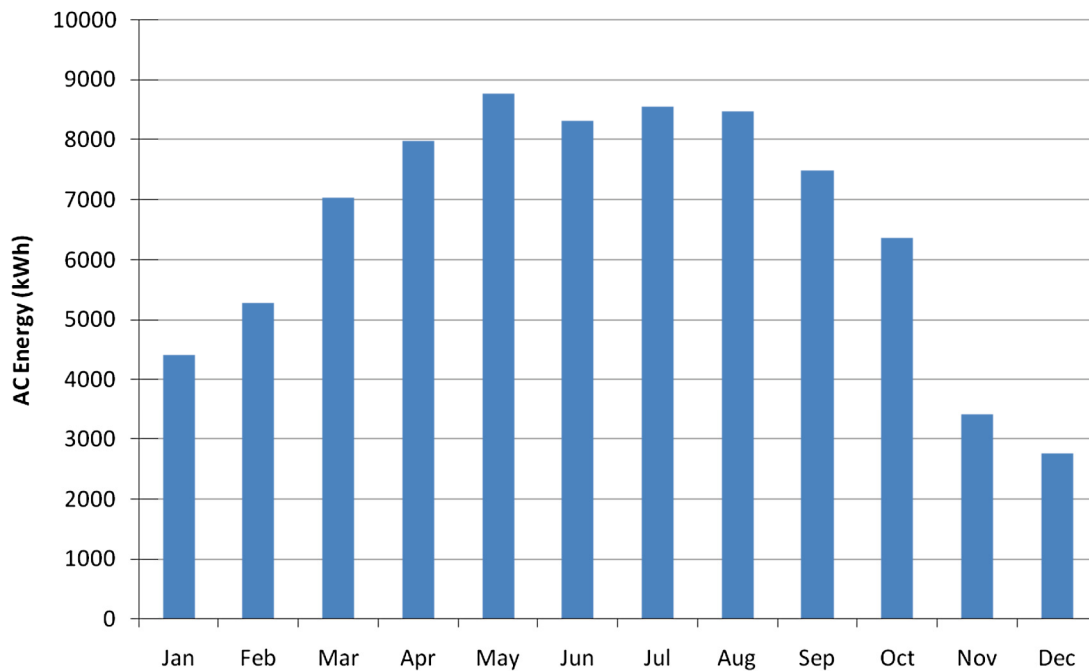


Figure 1.—Predicted AC Energy for a Grid-Tied 72 kW DC Photovoltaic Power System in Cleveland, Ohio.

TABLE 2.—PREDICTED ANNUAL AC ENERGY FOR A GRID-TIED 72 kW DC PHOTOVOLTAIC POWER SYSTEM

City	Tilt, degrees	Annual AC energy, kWh
Cleveland	41.4	78797
Tampa	28.0	98197
Los Angeles	33.9	105821
Phoenix	33.4	116421
Las Vegas	36.1	119775
Anchorage	61.2	57173
Montreal	45.5	79236
Berlin	52.5	54304
Matsumoto	36.2	85240
Moscow	55.8	55214
Paris	48.7	58723

The predicted annual AC energy produced from a grid-tied 72 kW DC PV power system for different areas throughout the world are shown in Table 2. The assumptions made for this prediction is that the PV array is crystalline silicon, the PV array tilt is fixed at the appropriate angle for the specific location, the PV array azimuth is 180.0°, and the DC-to-AC derating factor is 0.770. It is interesting to note from the world comparison that Cleveland is a viable location for PV energy production, with potentially significantly greater annual energy production than Berlin, Moscow or Paris for the same PV system properly oriented for the specific location. In addition, the potential annual energy production from the same PV system in Cleveland is not significantly less than such a system located in Tampa.



## Hardware Description

### GRC West Area Photovoltaic Power System

The NASA Glenn Research Center (GRC) designed, developed, and installed, a 37.5 kW DC photovoltaic (PV) Solar Field in the GRC West Area in the 1970s for the purpose of testing PV panels for various space and terrestrial applications. The PV panels are arranged to provide a nominal 120 VDC. The existing Solar Field is shown in Figures 2 and 3. The system block diagram is shown in Figure 4. System component specifications are included in the Appendix. The GRC Solar Field has been extremely successful in meeting its mission. The PV panels and the supporting electrical systems are all near their end of life. GRC has designed a 72 kW DC grid-tied PV power system to replace the existing GRC West Area Solar Field.



Figure 2.—Front View of the Existing GRC West Area Solar Field.



Figure 3.—Rear View of the Existing GRC West Area Solar Field.

#### ENERGY FLOW

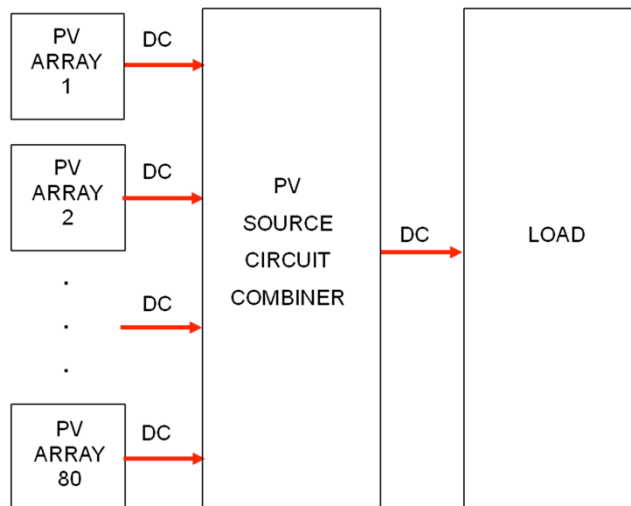


Figure 4.—Existing GRC West Area Solar Field.

#### ENERGY FLOW

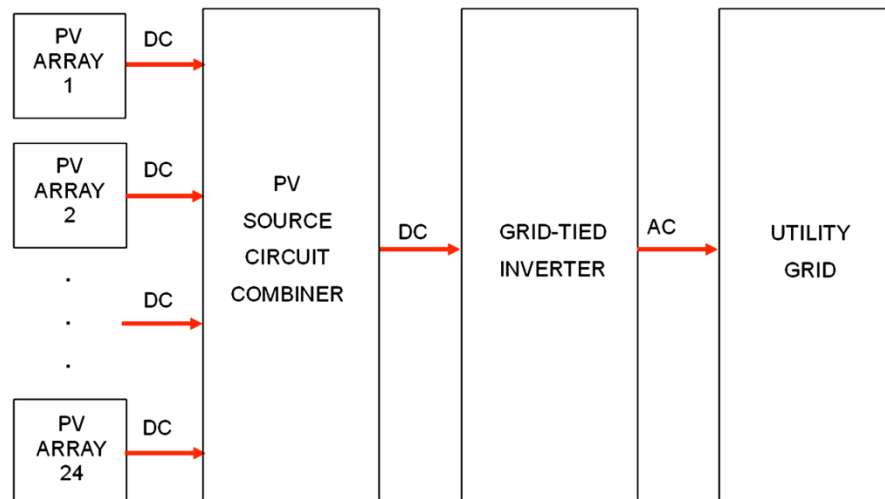


Figure 5.—Proposed GRC West Area 72 kW Grid-Tied Photovoltaic System Block Diagram.

The 72 kW DC grid-tied PV power system will provide DC solar power for GRC PV testing applications, and provide AC facility power for all times that research power is not required. A grid-tied system is connected directly to the utility distribution grid. Facility power can be obtained from the utility system as normal. The PV system is synchronized with the utility system to provide power for the facility, and excess power is provided to the utility for use by all. The 72 kW DC grid-tied PV power system hardware includes the photovoltaic panels, a source circuit combiner, and the DC/AC inverter. The design of the system is based upon the GRC prototype 2 kW grid-tied photovoltaic power system that has been operating flawlessly at GRC since 2006 (Ref. 4), as well as the GRC Visitor's Center grid-tied photovoltaic power system that has been operating equally as well at GRC since 2008 (Ref. 5). The 72 kW DC grid-tied PV power system block diagram is shown in Figure 5. System component specifications are included in the Appendix.

The photovoltaic panels selected for the 72 kW DC grid-tied PV power system are semiconductor panels that convert energy from sunlight to DC electrical power. The panels are unbreakable and maintenance free. The system consists of 360 solar panels, each rated for 200 W DC at 27.1 V. Each panel consists of 54 silicon poly-crystalline cells in series. The panel efficiency in providing power from the sunlight is rated at 15 percent. Each panel weighs 39 lb, and is 58.5 by 38.6 in. The life expectancy of the PV panels is 25 years or greater. The support structure for the panels is a fixed mount to orient the panels southerly with a tilt of 41.4° from horizontal to align the panels for the latitude of Cleveland, Ohio. Solar trackers are available to increase the available power from the Sun. Under ideal conditions, a tracker can provide up to 50 percent additional daily power from a PV array. In temperate latitudes, a tracker can provide an annual 25 percent increase in power from a PV array. Numerous technologies are available for trackers, including electric drives and fluid drives. Trackers are mechanical devices, and thus have potential life and maintenance issues. To avoid life and maintenance concerns, a fixed mount was selected for the GRC West Area 72 kW PV power system design.

The 360 PV panels are configured as 24 sets of 15 panels in series. Each of the 24 circuits is connected to a source circuit combiner. The combiner provides 15 A fuse protection for each of the circuits. The combiner weighs 45 lb, and is 20 by 20 by 6 in. The output of the combiner is a single DC output that feeds the photovoltaic inverter. The selected inverter converts the DC electrical power derived from the photovoltaic panels to three phase, 60 Hz, sinusoidal AC power synchronized to the AC utility power system. The inverter is rated at 75 kW, 480 VAC three phase with an efficiency of 95.5 percent. The inverter weighs 2,750 lb, and is 35.0 by 92.4 by 62.6 in. The life expectancy of the inverter is 20 years or greater.

The GRC West Area 72 kW PV power system was designed per the National Fire Protection Association (NFPA) 70, the National Electrical Code (NEC). The system concurs with all articles of the NEC, and in particular addresses Article 690, Solar Photovoltaic Systems. In addition, the system was designed to be completely in concurrence with the NASA GRC Safety Manual. The PV panels meet the requirements of Underwriters Laboratories Standard for Safety UL-1703 concerning flat-plate PV modules and panels. The PV panels are fused to provide overcurrent protection. The PV panels, and the entire PV system, are bonded and grounded per the NEC. The PV inverter includes an NEC compliant DC and AC disconnect switch to provide complete system isolation whenever the disconnect switch is opened. The inverter is configured to automatically open the inverter circuits whenever utility power is lost to prevent power from the PV system from feeding back into the utility power system, thus preventing a potential safety hazard.

## **Discussion**

The objective of designing the GRC West Area 72 kW grid-tied photovoltaic power system is to develop a photovoltaic power system that can be used for the testing of PV systems for research applications, and to provide power to the GRC utility grid when research is not being conducted that can be used by all.

The predicted annual energy production from the 72 kW PV power system is 78,797 kWh, which is a realistic prediction based upon the test results from the GRC prototype 2 kW grid-tied PV power system (Ref. 4), and the GRC Visitor's Center grid-tied PV power system (Ref. 5). The long-term system performance of GRC's existing PV power systems provides confidence in the integrity of the design of the GRC West Area 72 kW PV power system.

The rather large predicted monthly variation in energy production of the GRC West Area 72 kW PV power system shown in Figure 1 indicates the large seasonal variation in sunlight in Cleveland, Ohio. A grid-tied PV power system is advantageous in regions, such as Cleveland, in which utility power is essential in times of limited sunlight to meet the power requirements of the load. The significant power produced by the PV power system in the summer months is valuable in meeting the high utility system power demand at that time.

The monthly energy production of the GRC prototype 2 kW PV power system over the past four years indicates very consistent long-term system performance (Ref. 4). No effort was made to clean the PV panels, or to clear them of snow for these tests. Providing cleaning and snow clearing of the PV panels would improve PV system performance, but the test results obtained without cleaning or snow clearing indicates the excellent performance attainable from this system under no maintenance conditions. No planned maintenance is required for the GRC West Area 72 kW PV power system.

The GRC prototype 2 kW PV power system has provided consistent long-term PV system performance over the past four years with no system failures, no down time, and no required system maintenance (Ref. 4). Excellent system performance is predicted for the GRC West Area 72 kW PV power system as well.

## **Concluding Remarks**

The NASA Glenn Research Center has successfully designed, developed, analyzed, and tested a prototype 2 kW DC grid-tied photovoltaic power system, and a 12 kW DC grid tied photovoltaic power system. A 72 kW DC grid-tied photovoltaic power system was designed for the GRC West Area Solar Field based upon the success of the existing grid-tied photovoltaic power systems. The goals of the project include reducing the Nation's dependence on fossil fuels, and reducing the production of harmful emissions. The objective of this work is to develop a viable 72 kW DC grid-tied photovoltaic power system that can be used for GRC PV testing applications and to provide AC facility power for all times that PV research power is not required. The GRC West Area 72 kW grid-tied photovoltaic power system will validate the theoretical analyses, and verify long-term system performance.

Theoretical analyses have been performed successfully to predict the energy produced by grid-tied PV systems in Cleveland, Ohio. Empirical test results obtained from the experimental hardware successfully validated the basic principles described, and the theoretical work that was performed. Of particular value, are the analytical tools and capability successfully used for this project. Performance predictions can be made confidently for grid-tied PV systems of various scale.

The prototype 2 kW DC grid-tied PV system has provided consistent long-term performance over the past four years with no system failures, no down time, and no required system maintenance (Ref. 4). The GRC Visitor's Center 12 kW DC grid-tied PV system has been equally successful for over one year (Ref. 5). From the analyses and empirical test results, it is apparent that grid-tied PV systems are viable in Cleveland, Ohio.

The report concludes that the implementation of grid-tied photovoltaic power systems can provide significant improvements in power system performance, reduce dependency on fossil fuels, and reduce the production of harmful emissions. A GRC West Area 72 kW grid-tied PV system is a valuable tool for PV research for space and terrestrial applications, and is an efficient, reliable, and maintenance free source of power for GRC and the local community.

## Appendix—Equipment Summary Data Sheet

### Existing GRC West Area Solar Field Photovoltaic System

1.0	Photovoltaic Panels	
1.1	Type	Silicon Poly-Crystalline
1.2	Nominal Power	43 W
1.3	Max Power Voltage (Vmp)	17.3 V
1.4	Max Power Current (Imp)	2.49 A
1.5	Open Circuit Voltage (Voc)	21.7 V
1.6	Short Circuit Current (Isc)	2.7 A
1.7	Nominal Operating Cell Temp (NOCT)	47.0 °C (116.6 °F)
1.8	Nominal Power at NOCT	39.1 W
1.9	Max Power Voltage at NOCT	15.3 V
1.10	Max Power Current at NOCT	2.56 A
1.11	Open Circuit Voltage at NOCT	20.0 V
1.12	Short Circuit Current at NOCT	2.77 A
1.13	Short Circuit Current Temp Coefficient per Cell	2.0 mA/°C
1.14	Open Circuit Voltage Temp Coefficient per Cell	−2.5 mV/°C
1.15	Cell Area	3.61 sq ft
1.16	Cell Efficiency	12.8%
1.17	Module Efficiency	11.5%
1.18	Width	30.5 cm (12.0 in.)
1.19	Length	12.2 cm (48.0 in.)
1.20	Depth	6.4 cm (2.5 in.)
1.21	Weight	5.9 kg (13.0 lb)

## Proposed GRC West Area Grid-Tied Photovoltaic Power System

### 1.0 Photovoltaic Panels

1.1	Type	Silicon Poly-Crystalline
1.2	Peak Power (Wp)	200 W
1.3	Max Power Voltage (Vmp)	27.1 V
1.4	Max Power Current (Imp)	7.4 A
1.5	Open Circuit Voltage (Voc)	34 V
1.6	Short Circuit Current (Isc)	7.8 A
1.7	Short Circuit Temp Coefficient	5.6 mA/°C
1.8	Open Circuit Voltage Coefficient	−0.12 V/°C
1.9	Max Power Temp Coefficient	−0.5%/°C
1.10	Max Series Fuse	15.0 A
1.11	Normal Operating Cell Temp (NOCT)	45.0 °C (113 °F)
1.12	Width	98.1 cm (38.6 in.)
1.13	Length	148.5 cm (58.5 in.)
1.14	Depth	5.5 cm (2.2 in.)
1.15	Weight	17.7 kg (39.0 lb)

### 2.0 Source Circuit Combiner

2.1	Type	Parallel
2.2	Number of Input Circuits	18 to 24
2.3	Voltage Rating	600 VDC Continuous
2.4	Current Rating	400 ADC Continuous
2.5	Input Conductor Size	No. 16 to 4 AWG
2.6	Maximum Fuse Rating	20 A
2.7	Number of Output Conductors	2
2.8	Output Conductor Size	No. 4 AWG to 350 MCM
2.9	Enclosure Type	NEMA 3R (outdoor rated)
2.10	Width	50.8 cm (20.0 in.)
2.11	Height	50.8 cm (20.0 in.)
2.12	Depth	15.2 cm (6.0 in.)
2.13	Weight	20.4 kg (45.0 lb)

## 2.0 Inverter

2.1	Type	Three Phase Sine Wave
2.2	Max AC Power Output	75000 W
2.3	Maximum DC Input Voltage	600 VDC
2.4	DC Peak Power Tracking Range	295 to 500 VDC
2.5	DC Nominal Current	267 A
2.6	Nominal AC Output Voltage	480 VAC
2.7	AC Operating Voltage Range	422 to 528 VAC
2.8	Nominal AC Frequency	60 Hz
2.9	Max Continuous Output Current	90 A
2.10	Max Total Harmonic Distortion	≤3%
2.11	Power Factor	>0.99
2.12	Peak Inverter Efficiency	95.5%
2.13	Standby Losses	42 W
2.14	Output Overcurrent Protection	25 A
2.15	Operating Temperature Range	−30 to 50 °C (−22 to 122 °F)
2.16	Enclosure Type	NEMA 4 (outdoor rated)
2.17	Disconnect	PV/Utility disconnect
2.18	Cooling	Forced Convection
2.19	Width	159.0 cm (62.6 in.)
2.20	Height	234.7 cm (92.4 in.)
2.21	Depth	88.9 cm (35.0 in.)
2.22	Weight	1247.4 kg (2750 lb)

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<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> <p>The NASA Glenn Research Center (GRC) designed, developed, and installed, a 37.5 kW DC photovoltaic (PV) Solar Field in the GRC West Area in the 1970s for the purpose of testing PV panels for various space and terrestrial applications. The PV panels are arranged to provide a nominal 120 VDC. The GRC Solar Field has been extremely successful in meeting its mission. The PV panels and the supporting electrical systems are all near their end of life. GRC has designed a 72 kW DC grid-tied PV power system to replace the existing GRC West Area Solar Field. The 72 kW DC grid-tied PV power system will provide DC solar power for GRC PV testing applications, and provide AC facility power for all times that research power is not required. A grid-tied system is connected directly to the utility distribution grid. Facility power can be obtained from the utility system as normal. The PV system is synchronized with the utility system to provide power for the facility, and excess power is provided to the utility for use by all. The project transfers space technology to terrestrial use via nontraditional partners. GRC personnel glean valuable experience with PV power systems that are directly applicable to various space power systems, and provide valuable space program test data. PV power systems help to reduce harmful emissions and reduce the Nation's dependence on fossil fuels. Power generated by the PV system reduces the GRC utility demand, and the surplus power aids the community. Present global energy concerns reinforce the need for the development of alternative energy systems. Modern PV panels are readily available, reliable, efficient, and economical with a life expectancy of at least 25 years. Modern electronics has been the enabling technology behind grid-tied power systems, making them safe, reliable, efficient, and economical with a life expectancy of at least 25 years. The report concludes that the GRC West Area grid-tied PV power system design is viable for a reliable, maintenance free, long life power system that is of significant value to NASA and the community.</p>					
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